# Application of Non-coherent Doppler Data Types for Deep Space Navigation

Shyam Bhaskaran

Jet Propulsion Laboratory

California Institute of Technology

Pasadena, California

### Abstract

Recent improvements in computational capability and DSN technology have renewed interest in examining the possibility of using one-way Doppler data alone to navigate interplanetary spacecraft. The one-way data can be formulated as the standard differenced-count Doppler or as phase measurements, and the data can be received at a single station or differenced if obtained simultaneously at two stations. A covariance analysis is performed which analyzes the accuracy obtainable by combinations of one-way Doppler data and compared with similar results using standard two-way Doppler and range. The sample interplanetary trajectory used was that of the Mars Pathfinder mission to Mars. It is shown that differenced one-way data is capable of determining the angular position of the spacecraft to fairly high accuracy, but has relatively poor sensitivity to the range. When combined with single station data, the position dispersions are roughly an order of magtude larger in range and comparable in angular position as compared to dispersions obtained with standard data two-way types. It was also found that the phase formulation is less sensitive to data weight variations and data coverage than the differenced-count Doppler formulation

## I  Introduction

With increasing emphasis on controlling the costs of deep space missions, several options are being examined which decrease the costs of the spacecraft itself. One such option is to fly spacecraft in a non-coherent mode, that is, the spacecraft does not carry a transponder capable of coherently returning a carrier signal. Historically, one-way Doppler data have not been used as the sole data type due to the instability of spaceborne oscillators, the use of S-band frequencies, and the corresponding error sources which could not be adequately modelled. However, with the advent of high-speed workstations and more sophisticated modelling ability, the possibility of using one-way Doppler is being re-examined. This paper assesses the navigation performance of various one-way Doppler data types for use in interplanetary missions. As a representative interplanetary mission, the Mars Pathfinder spacecraft model and trajectory were used to perform the analysis. Comparisons are given between results employing Doppler data formulated as standard differenced-count Doppler (which yields a frequency measurement) as well as accumulated carrier phase (which yields a distance measurement, usually given in terms of cycles). Combinations of one-way data obtained simultaneously at two different stations and then differenced (to produce an angular type measurement) and single station one way data are shown to produce results whit.], may satisfy future mission requirements.

## II  Spacecraft Trajectory

In order to perform the analysis, a representative interplanetary trajectory was needed. The one used in this study is the Mars Pathfinder cruise from Earth to Mars. The spacecraft is injected into its trans-Mars trajectory 011 January 3, 1997, and reaches Mars on July 4, 1997. A schematic of this trajectory is shown in Figure 1. In between, there are four Trajectory Correction Maneuvers (TCMs) (on February 2, March 3, May 5, and June 24), with mean magnitudes of 22.1, 1.4, 0.2, and 0.1 111/s, respectively. The first two are to remove an injection targeting bias which the initial interplanetary trajectory contains in order to satisfy planetary quarantine
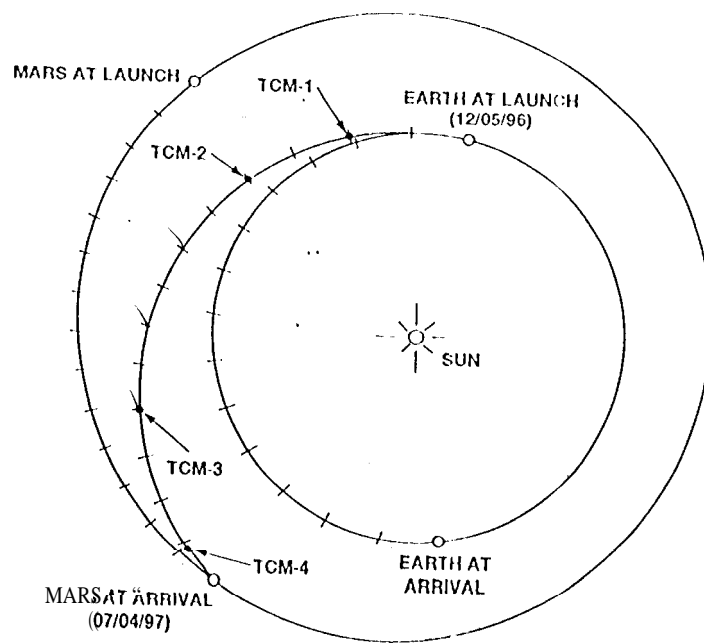
Mars Pathfinder Trajectory
(provided by P. H. Kallemeyn, Mars Pathfinder Navigation)

requirements. The final two are used to precisely target the spacecraft for its final approach and entry into the Martian atmosphere. Since Pathfinder goes directly from its interplanetary trajectory to atmospheric entry, the aim point of the targeting maneuvers is chosen such that the entry flight path angle is between 14.5° and 16.5°1. This corresponds to an entry corridor in the B-plane of about 50 km wide in the cross-track direction. The downtrack and normal direction constraints are chosen to ensure that the spacecraft reaches the landing site with a 99% probability of being within a 200 km downtrack by 1O(I km crosstrack ellipse[1].

## 111 Doppler **Measurement** Model

When operating in one-way mode, the DSN measures the Doppler frequency of the carrier signal received from a spacecraft by comparing it with a reference frequency generated by a local oscillator. The two signals are differenced, and a counter measures the accumulated phase of the resultant signal over set periods of time, called the count time. The total phase change over the count time, divided by the count time, produces a measure of the Doppler shift of the incoming signal, with which the range rate of the spacecraft can be inferred. This is referred to as differenced-count Doppler, the standard measurement used for all deep space missions thus far. If instead, the original phase data themselves are used, a measure of the change in the range of the spacecraft over the length of the pass is obtained, with the initial range at the start of the pass being an unknown. Although in principle this a fairly powerful data type, it has not been used in the past due to operational problems associated with cycle slips, whereby the receiver momentarily loses lock with the incoming signal. Advances in technology over the years, however, have made cycle slips less frequent, and thus there is renewed interest in examining the possibility of using the phase measurement directly as a data type

The four data types investigated in this study were one-way Doppler, one-way differenced Doppler, one-way phase, and one-way differenced phase. In order to obtain a qualitative understanding of what information is

11'. H. Kallemeyn, Mars Pathfinder Navigation Plan, J}'],-]) 11349, July, 1994

available with these data, some simple equations will be presented. Neglecting error sources and relativistic effects for the moment, one-way Doppler data is approximately proportional to the topocentric range-rate of a spacecraft:

$$f \approx f_T(\dot{\rho}/c) \tag{1}$$

where

$f$ = the observed Doppler shift of the carrier signal

$f_T$ = the carrier frequency t ransmitted by the spacecraft

$\dot{\rho}$ = the station-spacecraft range rate, and

$c$ = the speed of light.

Hamilton and Melbourne [1] derived a simple approximation for the topocentric range rate seen at a tracking station in terms of the cylindrical coordinates of the station and t he geocentric range rate, right ascension, and declination of the spacecraft:

$$\dot{\rho} \approx \dot{r} + \omega r_s \cos\delta \sin(\omega t + \alpha_s + \lambda_s - \alpha) \tag{2}$$

where

$\dot{r}$ = the geocentric range rate of the spacecraft

$\alpha, \delta$ = the geocentric right ascension and declination of the spacecraft

$\omega$ = the rotation rate of the earth

$\alpha_s$ = the right ascension of the sun

$r^*, \lambda_s$ = the spin radius and longitude of the station.

Thus, the signal seen at the station represents the sum of the geocentric velocity of the spacecraft and short term sinusoidal variations due to the rotation of the Earth. The amplitude of the sinusoidal variation is proportional to the cosine of the declination of the spacecraft, and its phase includes information about the right ascension. Now, if the signals received simultaneo usly at two stations are differenced, the geocentric range rate drops out of the equation and only the periodic variations are left. This implies that differenced Doppler data are incapable of directly measuring the range of the spacecraft, but can better resolve its regular position than the undifferenced data. In addition, the differenced data are nearly insensitive to short term variations in the velocity, such as those due to short thruster firings.

If eqn. (1) is now integrated over the interval from $t_0$ to $t$, the following expression for the Doppler phase is obtained:

$$\phi_t - \phi_{t_0} \approx f_T(\rho_t - \rho_{t_0})/c \tag{3}$$

where

$\rho$ = the topocentric range of the spacecraft at times $t$ and $t_0$, and

$\phi$ = the measured phase of the carrier signal at times $t$ and $t_0$.

Thus, the phase of the received carrier signal at a given time measures the change in range from the previous time. At the beginning of the pass, there will be an unknown bias representing the initial range to the spacecraft. An u analytical app roximation for the difference of two range measurements received simultaneously at two stations can be written in terms of the baseline vector between them as [2]:

$$\Delta\rho \approx r_B \cos\delta \cos(\alpha_B - \alpha) + z_B \sin\delta \tag{4}$$

where

$r_B$ = baseline component normal to the Earth's spin axis

$z_B$ = baseline component parallel to Earth's spin axis

$\alpha_B$ = the baseline right ascension

$\alpha$ = the spacecraft right ascension

$\delta$ = the spacecraft declination.

3

Once again, it can be seen that differencing the data removes direct information about the radial distance to the spacecraft and the result is given in terms of its angular position.

All data used in this analysis were assumed to be obtained at X-band frequencies (7.2-8.4 GHz). The differenced data types were taken when the spacecraft was visible simultaneously from two DSN stations above an elevation cutoff of 15 degrees. This resulted in overlaps of roughly four hours in length occurring over the Goldstone-Madrid and Goldstone-Canberra baselines throughout the data tire. No data over the Canberra-Madrid baseline could be obtained.

Data scheduling was set, as follows. Single station one-way data were taken during every other pass at all three DSN sites, starting at the beginning of the Mars Pathfinder trajectory (January 3, 1997) aud ending at the data cutoff 011 June 19, 1997. This results in roughly 14,000 points (at 10 minute intervals). Two-station differenced data was scheduled at every overlap until the data cutoff date, resulting in approximately 6000 points. The assumed noise levels used were 0.1 and ).0 cycles for phase data, and 0.05 and 0.5 mm/s for the Doppler data.

# IV Orbit Determination Error Analysis

Orbit determination is composed of several steps: generation of a reference trajectory, compution of observational partial derivatives with respect to the reference trajectory, and correction of the trajectory and error model parameters using an estimation algorithm, or filter. The associated error covariance of the estimated parameters is also obtained as part of this procedure. The error covariance analysis was performed using a modified version of JPL's DPTRAJ/ODP software called MIRAGE [3]. MIRAGE offers au improvement over the ODP in that it is capable of modelling time varying stochastic parameters which have different "batch" lengths, that is, time steps over which the parameters are piecewise continuous.

In order to obtain a realistic estimate of the covariance, the dynamic forces affecting the spacecraft and the error sources affecting the data must be modelled properly. A detailed analysis of these model parameters has already been performed for the Mars Pathfinder mission[2], the results will be summarized here. In the filter model, all known dynamic parameters and significant, Doppler error sources are modelled and explicitly estimated. The dynamic parameters included the spacecraft state (position and velocity), coefficients for solar radiation pressure, random non-gravitational accelerations, and spacecraft maneuvers. The solar radiation pressure and random accelerations each have three components: a radial one along the earthline and two cross line-of-sight ones which are mutually orthogonal to the radial direction. These are modelled as stochastic Gaussian colored noise parameters, that is, an estimate is made for the parameters within each batch, and their values from one batch to another are statistically correlated with a characteristic decorrelation time input by the user. The solar radiation pressure coefficients vary slowly over the course oft he mission as tlIc reflectivity of the spacecraft changes so the decorrelation time of these parameters was set to 60 days. The uncertainties are roughly 5% of the nominal values of the coefficients. Stochastic accelerations are needed to model small thruster firings, such as those used for attitude updates. The size and frequency of these firings results in accelerations with decorrelation times of 5 to 6 days and an rms magnitude of about $2x10^{-12}$ km/s$^2$ in the radial direction and $1x10^{-12}$ km/s$^2$ in the crosstrack directions. Spacecraft maneuvers are deterministic in nature and, in general, can be model led as impulsive velocity changes placed at the midpoint of the maneuver time. Experience on previous missions has shown that the maneuver magnitude can be controlled to around 1% accuracy, so the a-priori uncertainty in the maneuver parameters was set, to 1% of the expected size of the AV for each midcourse maneuver. No constraints were placed on the direction. Table 1 summarizes all of the statistical values used in the filter.

Error sources which affect the data include media calibration errors (wet and dry troposphere, day and night ionosphere), solar plasma effects, Earth platform calibration errors (station location in cylindrical coordinates, pole location in cart esian x and y coordinates), and Earth rotation (UTC). The delays in the signal caused by its path through the troposphere and ionosphere are modelled, but er rors still remain. Currently, the troposphere model is good to 5 cm and the ionosphere to 3 cm [4]. The errors vary at a relatively high frequency, and so the decorrelation time is set to a few hours. The station location set and its associated uncertainties are the DE 234 coordinates developed for use by the Mars Observer (M()) misssion.[3] The station location uncertainties were

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[2] S. W. Thurman,̋ Orbit Determination Filter and Model ing Assumptions for MESUR Pathfinder Guidance and Navigation], Analysis,̋ JPL-IOM 314.3-1075, October 15, 1993

[3] W. M. Folkner, "DE 234 Station Locations and Covariance for Mars Observer,̋ JPL IOM 33EI,I-92-(113. May 26, 1992.

Table 1: A-priori $1\sigma$ Uncertainties of Filter Parameters

| Parameter | A-priori Uncertainty | Correlation Time |
|---|---|---|
| Position $(x, y, z)$ | 100.0 km | - |
| Velocity $(\dot{x}, \dot{y}, \dot{z})$ | 1.0 m/s | - |
| Solar Radiation Pressure Coefficient (radial) | 0.07 | 60 days |
| Solar Radiation Pressure Coefficient (cross line-of-sight) | 0.02 | 60 days |
| Stochastic Acceleration (radial) | $2.4 \times 10^{-12}$ mm/s$^2$ | 5 days |
| Stochastic Acceleration (cross line-of-sight) | $0.8 \times 10^{-12}$ mm/s$^2$ | 5 days |
| Maneuvers | 1% of nominal value | - |
| Station Locations (spin radius, z-height, longitude) | 0.1 m | - |
| Troposphere (wet) | 5 cm | 2 hours |
| Dry Troposphere (dry) | 5 cm | 2 hours |
| Ionosphere (day) | 3 cm | 4 hours |
| Ionosphere (night) | 1 cm | 1 hour |
| Pole X and Y | 0.1 m | 2 days |
| Earth Rotation (UTC) | 0.15 m | 1 day |

modified to approximately account for precession and nutation modelling errors as well. These values are assumed fixed for the duration of the Pathfinder trajectory. The polar motion and UTC variations can be predicted by the DSN to a level of around 10 to 15 cm, and they vary on the order 1 to 2 days. The a-priori uncertainties of these error model parameters, along with their characteristic decorrelation time if they are stochastic variables, are also shown in Table 1. One point to note is that the Mars ephemeris uncertainties were not included in the filter. This was done so that the computed dispersions reflect only the strengths and weaknesses of the data in determining the spacecraft trajectory.

When one-way Doppler data are used, several additional error sources must also be taken into account. For single station data, the largest error source is the frequency drift of the spacecraft oscillator. Ultra Stable Oscillators of the class used by the Galileo and Mars Observer spacecraft are expected to be stable to around 1 part in $10^{12}$ over time spans of around a day. Over longer time spans, however, the frequency will wander ant] must be modelled. The method used to model this error source is to treat the bias as a random walk parameter. Qualitatively, the random walk model allows the parameter to move away from its value at the previous batch time step by an amount constrained by its given a-priori uncertainty. It differs from a Gaussian white or colored noise stochastic parameter in that the parameter dots not simply oscillate around its mean value, but is allowed to wander from one time step to the next. This model was also intended to approximately account for solar plasma fluctuations, which induce frequency variations on the order of 1 part in $10^{-4}$ over one day. For this study, a fairly modest stability of 1 part in $10^9$ over the course of a day was assumed to be the nominal. The value for the oscillator bias is updated every hour, and its a-priori sigma corresponds to the change in frequency over an hour expected for the given stability.

The one-way Doppler phase formulation requires six additional parameters in the estimate list. Phase data is measured by counting the integer number of zero crossings of the signal; a resolver then determines the fractional portion of the phase at a given time. Initially, however, there will be an ambiguity in the number of cycles it took for the signal to reach the ground, and the phase when the receiver locks onto the signal. To account, for this, a phase bias at all three DSN stations is included in the filter. The a-priori uncertainty of the bias is set to 1000 cycles (essentially infinity), and the parameter is reset at the beginning of each pass. Also, during data acquisition, the station clocks have small drifts relative to a time standard which cause the phase count to drift as well. The drift is calibrated at the stations using data from the Global Positioning System, but residual errors remain. The magnitude with which the drift manifests itself in the phase count is about $6 \times 10^{-4}$ cycles/sec, so a phase drift parameter with this value for the a-priori uncertainty is also included in the filter. Once again, the parameter is reset at the beginning of each pass.

The primary advantage of using differenced data is that the spacecraft oscillator drift is effectively cancelled out when the single station Doppler data are differenced, thus removing a major error source. However, an additional error source will appear: the asynchronicity of the clocks at the two receiving stations. Currently, the

Table 2: A-priori 1 $\sigma$ Uncertainties of One-way Measurement Error Parameters

| Parameter | A-priori Uncertainty | Correlation Time |
|---|---|---|
| Frequency Bias | 0.366 Hz | Random walk, value reset every hour |
| Phase Bias | 1000 cycles | White noise, value reset at each pass |
| Phase Drift | $6.0 \times 10^{-4}$ cycles/s | White noise, value reset at each pass |
| Clock Offset | 5 nsec | White noise, value reset at each pass |

Table 3: 10 Dispersion Ellipses in Radial-Transverse-Normal Coordinat

| | Data Type(s) Used | Data Weight | $\sigma(RxTxN)$ (km) |
|---|---|---|---|
| 1 | 2-way Doppler | 0.05 mm/s | 3.9 x 6.4 x 7.2 |
| | + 2-way Range | 2.0111 | |
| 2 | Differenced 1 -way Phase | 0.1 cycles | 360.9 x 20.3 x 11.6 |
| 3 | Differenced 1-way Phase | 1.0 cycles | 476.8 x 23.9 x 12.1 |
| 4 | Differenced 1-way Doppler | 0.05 mm/s | 428.5 x 23.7 x 11.3 |
| 5 | Differenced 1-way Doppler | 0.5 mm/s | 1307.0 x 63.3 x 19.5 |
| G- | Differenced 1-way Phase | 0.1 cycles | 66.4 x 10.8 X-11.5 |
| | + 1-way Phase | 0.1 cycles | |
| 7 | Differenced 1-way Phase | 1.0 cycles | 68.7 x 12.1 x 12.1 |
| | + 1-way Phase | 1.0 Cycle> | |
| 8 | Differenced 1-way Doppler | 0.05 mm/s | 76.9 x 12.7 x 11.1" |
| | + 1-way Doppler | 0.05 mm/s | |
| 9 | Differenced 1-way Doppler | 0.5 mm/s | 254.1 x 33.7 x 18.7 |
| | + 1-way Doppler | 0.5 mm/s | |
| 10 | Differenced 1-way Phase | 0.1 Cycles | 6.7 x 8,3 X"]].] |
| | + 2-way Doppler | 0.05 mm/s | |
| 11 | Differenced 1-way Doppler | 0.05 mm/s | 6.8 x 8.4 x 10.8 |
| | -i 2-way Doppler | 0.05 mm/s | |
| 12 | 2-way Doppler | 0.05 mm/s | 14.4 x 14.4 x 23.7 |

clocks are calibrated to about the 5 nsec level (based on examination of Frequency and Timing Standard reports distributed weekly by the DSN) between each pair of stations. Thus, a parameter which represents this timing mismatch is added to the filter estimate list. In addition, the differenced phase data still requires parameters to model the phase bias and drift which, in this case, are errors in the differenced phase measurement due to relative clock drifts between the two station pairs. The magnitudes of the uncertainties are kept the same as before. All one-way measurement error parameters and uncertainties are summarized in Table 2.

# V Results

Although normally the results of a covariance analysis of an interplanetary trajectory are given in terms of encounter coordinates, the so-called B-plane system, it is more instructive in this case to present the uncertainties in radial-transverse-normal (RTN) coordinates. In RTN coordinates, the radial direction is along the Earth-spacecraft vector, the transverse direction is in the plane defined by the radius and the velocity vector, and the normal direction is perpendicular to both, forming an orthogonal triad. When viewed in this frame, it is easier to see in which direction the various data types have their greatest strength.

Table 3 shows the results of the covariance analysis in RTN coordinates for all combinations of data tried thus far. The first element in the table is a "nominal" result, using a standard tracking schedule for Pathfinder which includes standard two-way Doppler and range. It can be seen that the radial uncertainty is best determined, with the cross line-of-sight directions being marginally worse with a maximum uncertainty of 7.2 km. These results when mapped to the Mars B-plane are sufficient to meet the requirements of Pathfinder.

The second and third entries in the table were obtained using only one-way phase data, weighted at 0.1

and 1.0 cycles, respectively. The result clearly shows the ability of the differential data type to determine the angular position of the spacecraft as seen from the Earth. Using a data weight of 0.1 cycles, the normal direction is determined to 11.6 km, which compares fairly well with the 7.2 km result using Doppler and range. The uncertainty in the transverse direction does not compare quite as well, about a factor of three times worse than the nominal, but is still at a reasonable magnitude. The radial direction however, is very poorly determined, with the uncertainty using differenced phase data being about two orders of magnitude worse than the standard case. Changing the data weight from 0.1 to 1.0 cycles has little effect in the transverse and normal directions, but degrades the radial sigma by around 30%.

For comparison, the uncertainties using differenced one-way data formulated as Doppler frequency measurements were also examined (entries 4 and 5 in Table 3). The results are fairly similar to those of differenced phase data in the transverse and normal directions when the tighter data weight was used on the differenced Doppler. With the data weighted at 0.5 111111/s, however, the numbers are degraded considerably, especially in the radial direction.

Due to its inability to effectively discern the range to the spacecraft, it is highly unlikely that one-way differenced data alone would be sufficient to satisfy the navigation requirements of any realistic missions. It is desirable therefore to augment the differenced data with another data type, the obvious choice being single station one-way data. Entries 6 and 7 in Table 3 show the results of combining one-way phase with differenced phase at the two data weights. The effect is quite dramatic in the radial direction, with the uncertainty brought, down from 360.9 and 476.8 km to 66.4 and 68.7 km. This is still over an order of magnitude larger than the nominal case, but it is now at a level which could satisfy mission requirements. In the transverse direction, the uncertainties were brought down to very near the values of the nominal. The additional data had almost no effect in the normal direction. It is interesting to note that with the additional data, the data weight made very little difference in the final results.

The same effect is seen when one-way Doppler data is added to differenced one-way Doppler at the tight data weight (entry 8 of Table 3). The uncertainty values in the transverse and normal directions are. are now fairly close to those obtained with the phase data, and the radial sigma is only worse by around 15%. The case with the lower data weight (entry 9 of Table 3), however, does not show similar behavior. The radial sigma has been brought down by an order of magnitude, but its value is still too large to be of use in many missions.

Entries 10 and 11 in Table 3 snow the results of using differenced phase and 1 Doppler augmented by standard two-way Doppler data at a rate of one pass per week. This result is included to show what to expect if a spacecraft has a transponder onboard but with no ranging capability. These values indicate that navigation performance is only slightly degraded if two-way range is replaced by the differenced one-way data types. Comparison with the final entry in the table (2-way Doppler only) shows that the differenced data type improves the solution by a factor of two in all three components.

The results so far using one-way data assume a spacecraft oscillator stability of one in 109 over the course of a day. The question can then be raised as to how a better or worse oscillator would affect the orbit determination accuracies. The effect would be negligible if only the differenced data types were used, but it will make a difference when single station data is added. Figure 2 and Figure 3 present the results when the oscillator stability varies from one part in $10^7$ to one in $10^{14}$ over one day for the differenced phase plus phase, and differenced Doppler plus Doppler cases, respectively. In both cases, the tighter data weight was assumed. As can be seen from these plots, there is a sharp knee in the curve which takes place at around the $10^{10}$ value in the radial directions for both phase and Doppler. The transverse and normal sigmas change very little as a function of oscillator stability. At a stability level of 1012, the phase formulation case is now quite comparable in all three components to the standard two-way Doppler and range results, and the Doppler formulation is only slightly worse. Further improvements in stability do not seem to make much difference. This implies that a spacecraft carrying a USO of the class used by Galileo or Mars Observer can conceivably approach the navigation) accuracies achieved with two-way data types.

Another useful figure of merit is the amount of single station one-way data employed. The nominal results are based on a dense tracking schedule of using every other available pass. Figures 4 and 5 present the results if the amount of single station data is reduced to one pass per clay, one pass per Week, and one pass per month (the differenced data are assumed to remain at the nominal schedule, and the tight data weight was used). Once again, it can be seen that the transverse and normal sigmas are affected very little. The radial sigmas, however, show small changes when the data is thinned to once per day, and then a marked degradation when thinned
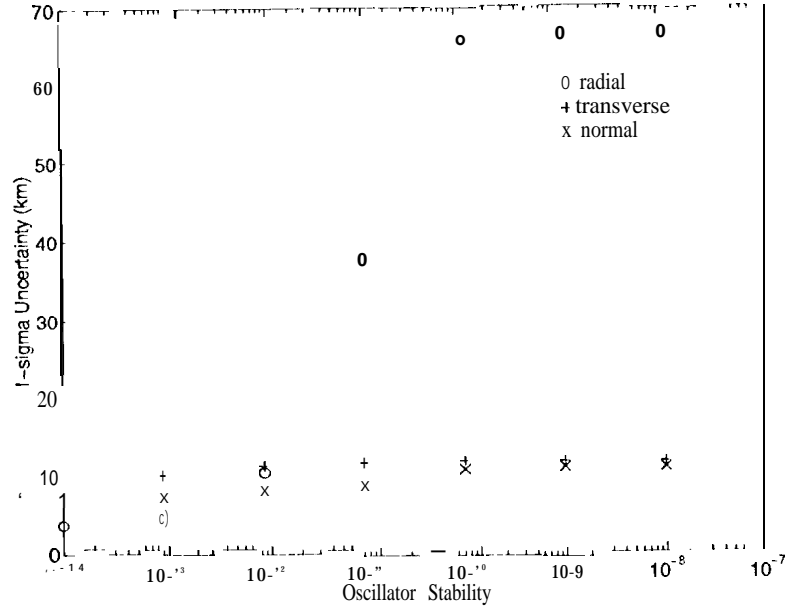
Figure 1: Sensitivity of Position Uncertainty to Oscillator Stability for Differenced Phase + Phase Data
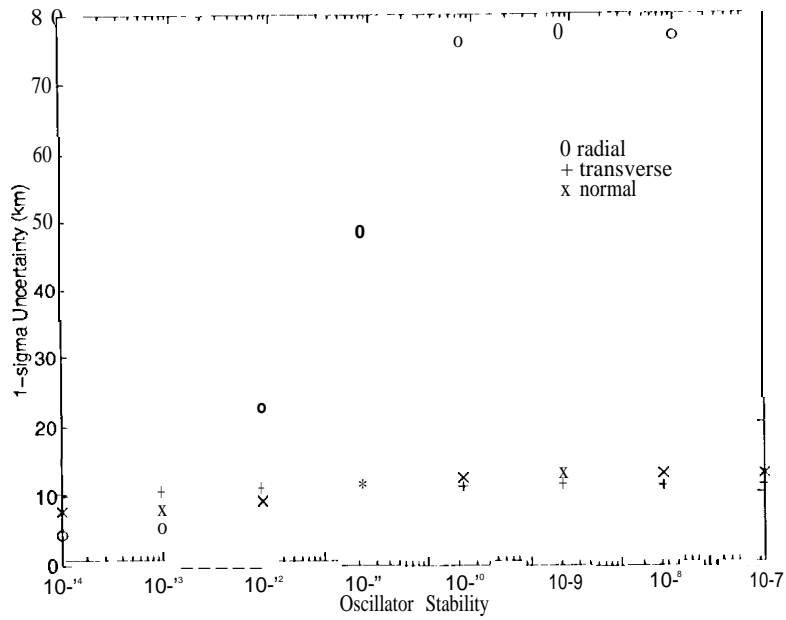


Figure 2: Sensitivity of Position Uncertainty to Oscillator Stability for Differenced Doppler -t Doppler Data
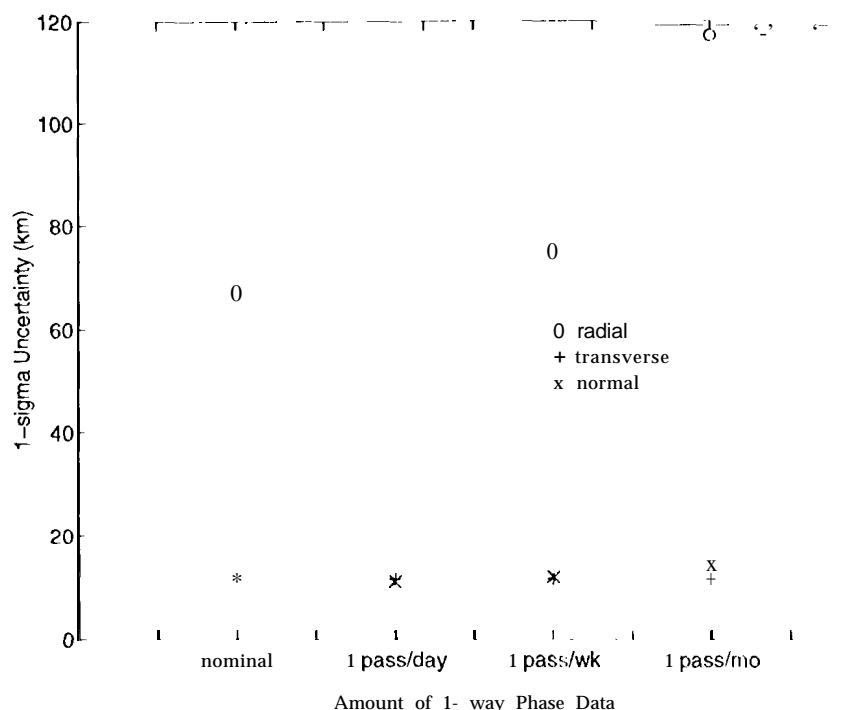
Figure 3: Sensitivity of Position Uncertainty to Amount, of Single Station Data (Coverage for Differenced Phase + Phase Data

further. The effect is more pronounced in the case of the differenced phase Doppler formulation, with the radial sigma dropping from its nominal value of around 80 km to a worst case of nearly 200 km. The phase formulation dots not suffer as much, as the decrease is only from 65 to 120 km.

# VI  Conclusions

The results of this study suggest that a combination of single station and two-station differenced one-way data types may be a realistic option for some interplanetary missions. This may be somewhat surprising because it has long been assumed that a very stable frequency is needed to render one- way data usable. However, it has been shown here that with a modest oscillator, reasonable results can be obtained by combining data which have different strengths and with the proper mathematical formulation of the data and filter. In particular, the estimation of the spacecraft's angular position in the sky can be nearly as good as with standard data types, although the spacecraft's radial position is relatively poorly determined. If a very good oscillator (stability of one part in $10^{12}$ over a day, or better) is available, then the accuracy in all three components may approach those obtained with standard navigation data types. One point to note, though, is that the oscillator stabilities were measured over a day. For a noncoherent system to be confidently used would require pre-flight testing of the oscillator over these time periods; something which has not been generally done in the past. Also, the results indicate that the phase formulation of Doppler data is superior in some respects to the differenced phase Doppler formulation in terms of navigation accuracies. At the tight data weights and with good data coverage, the values are comparable, but the phase data shows less sensitivity to decreasing data weights or coverage.

In practice, the choice of using non-coherent data types for navigation depends on the particular mission scenario and its requirements. In the case of the Mars Pathfinder mission, the geometry of the trajectory is such that the radial uncertainty maps almost completely into the time-of-flight direction (parallel to the incoming asymptote of the trajectory) in the Mars II-plane. Since the critical requirement is to maintain the proper entry angle (determined by the components perpendicular to the incoming asymptote), the degradation in performance is not severe. For example, if the entire Earth-Mars transfer were navigated using only differenced and single
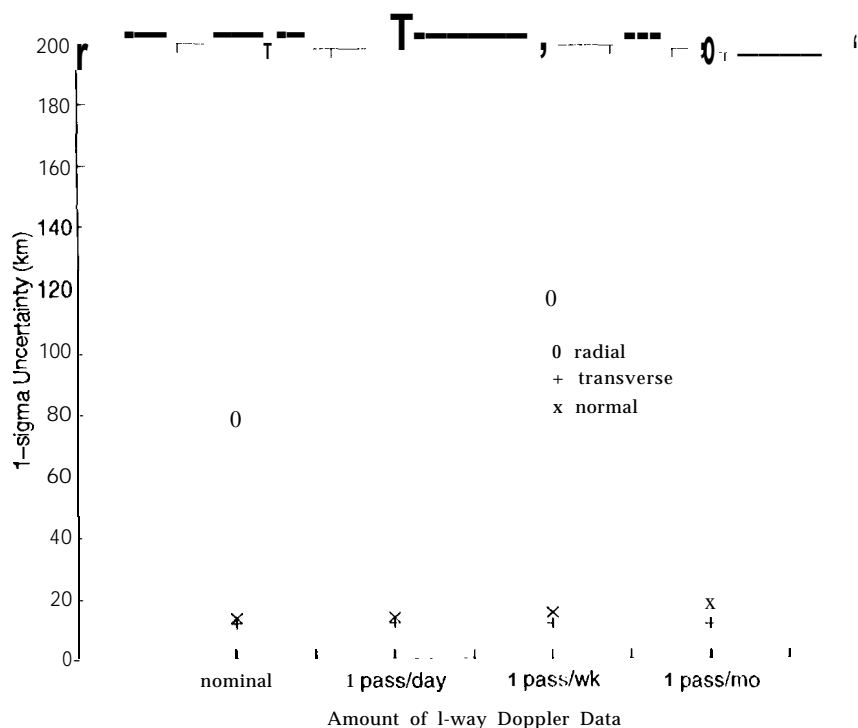
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Figure 4: Sensitivity of Position Uncertainty to Amount of Single Station Data Coverag e for Differenced Doppler + Doppler Data

station one-way phase, the probability of successful entry is still approximately 70%[4] (the probability is over 99% using two-way Doppler data). This value is obviously too low for Pathfinder to use non-coherent data as its baseline, but it is acceptable as a backup if the transponder fails. If tile spacecraft were to go into orbit, however, the navigatioi accuracies using non-coherent data might be adequate, depending on other factors such as propellant constraints, orbit maintenance requirements, etc. For missions whose geometry results in the radial sigma being of primary importance though, the switch to a non-coherent navigation system may not be advisable. Ultimately, the trade-off between cost and performance must be evaluated on a mission- by-mission basis, and no one answer is applicable to all cases.

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